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*(last revised February 2006)***Low-Energy Kaon-Nucleus Interactions at a ϕ -Factory***P.M. Gensini^{†‡}, G. Pancheri[§], Y.N. Srivastava[†] and G. Violini^{*}**[†]) Dip. di Fisica dell'Università di Perugia, Italy,
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and I.N.F.N., Laboratori Nazionali di Frascati, Gruppo Collegato di Cosenza, Italy.**[‡]) Speaker at the meeting.***ABSTRACT**

Scattering and formation experiments can be performed not only with particle beams, but also, as of old, with particle sources. DAΦNE at the c.m. energy of the ϕ is a relatively clean source of low-momentum charged and neutral kaons. As such, it can allow experiments unthinkable of at conventional kaon beams. This talk is dedicated to a presentation both of this viewpoint and of the physics that could be learned *only* in this way.

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Low-Energy Kaon-Nucleus Interactions at a ϕ -Factory

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1. Introduction.

We intend to illustrate in this proposal the possibilities on strangeness -1 , baryonic physics opened by the ϕ -factory DAΦNE¹, and in particular by its detector KLOE², considered as a huge (by design), active, gaseous ^4He target.

The interest in this field is of a systematic rather than exploratory nature: information on low-energy kaon-nucleon interactions is scarce and of a poor statistical quality, when compared to the corresponding pion-nucleon ones. As an example, just take a look at the two pages dedicated by the PDG booklet³ to $K^\pm p$ and $K^\pm d$ total and elastic cross sections: other data do not present a rosier perspective⁴.

The low quality of low-momentum elastic and inelastic scattering data reflects in turn on our knowledge of the “elementary” parameters of the KN interaction, remarkably poorer than in the $SU(3)_f$ -related πN case⁴. On top of this sorry situation, one must add the problem of fitting into the picture the kaonic hydrogen (and deuterium) level-shifts and widths, whose recent experimental determinations, despite having finally come out after many years with the sign (almost) every theorist expected⁵, are still awaiting an adequate explanation for their magnitude(s)⁶.

Data at very low momenta and at rest are essential to clarify many of the above-mentioned problems⁴; however, experiments of this kind pose formidable problems at conventional fixed-targeted machines, some of which can be circumvented at a ϕ -factory. For instance, at the KAON factory that was planned for TRIUMF⁷, beams in the lowest momentum range (from 400 to 800 MeV/c) would have had intensities of $10^6 - 10^8 \text{ K}^- \text{s}^{-1}$, with K^+ beams about twice more intense. Already the purity of these beams is limited by K^\pm decays in flight: to experiment at momenta below 400 MeV/c one has to use moderators, which at the same time decrease the kaon intensity, degrade the beam resolution, and increase enormously

the beam contamination at the final target. All these effects make the experiments much more complex, overturning all the advantages offered by the higher initial beam intensities.

2. Kaon–Nucleus Interactions at DAΦNE.

DAΦNE is the ϕ –factory (the acronym stands for “Double Annular Φ –factory for Nice Experiments”) of the I.N.F.N. National Laboratories in Frascati. From its expected commissioning luminosity⁸ of $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, and an annihilation cross section of about $5 \text{ } \mu\text{b}$ at the ϕ –resonance peak, one can see that its *two* interaction regions should have been the sources of $\simeq 1.2 \times 10^3 \text{ K}^\pm \text{ s}^{-1}$, at a central momentum of $126.9 \text{ MeV}/c$, with the momentum resolution of $\simeq 1.1 \times 10^{-2}$ due to the very small energy spreads in the beams, as well as of $\simeq 850 \text{ K}_L \text{ s}^{-1}$, at a central momentum of $110.1 \text{ MeV}/c$, with the slightly poorer resolution of $\simeq 1.5 \times 10^{-2}$.

Both π^\pm ’s and leptons coming out of the two sources are easy–to–control backgrounds: the first because the π^\pm ’s, though produced at a rate of about $380 \text{ } \pi^\pm \text{ s}^{-1}$ (not counting those from K_S decays), come *almost all* from events with three or more final particles and can thus be suppressed by momentum and collinearity cuts; the second, as well as collinear pions from $e^+e^- \rightarrow \pi^+\pi^-$, produced at much lower rates of order 0.75 s^{-1} (the leptons) or 0.25 s^{-1} (the pions), are eliminated by a momentum cut, having momenta about four times those of the K^\pm ’s.

The *two* interaction regions are therefore *small–sized* sources of *low–momentum, tagged* K^\pm ’s and K_L ’s, with *negligible contaminations* (after suitable cuts on angles and momenta of the particles are applied *event by event*), in an environment of very low background radioactivity: this situation is simply unattainable with *conventional* technologies at fixed–target machines⁹, where the impossibility of placing experiments too close to the production target limits from below the charged–kaon momenta, and kaon decays in flight always contaminate the beams: low–momentum experiments are thus possible only with the use of moderators, with a huge beam contamination at the target, as well as a large final–momentum spread due to straggling phenomena.

It is therefore of interest to consider the feasibility of low–energy, $K^\pm N$ and

$K_L N$ experiments at DAΦNE, with respect to equivalent projects at machines such as, e.g., the sadly aborted KAON at TRIUMF¹⁰ or the equally ill-fated EHF project¹¹.

We shall here try and give an evaluation of rates to be expected in a simple-geometry apparatus at DAΦNE, such as KLOE². We shall assume cylindrical symmetry, with a toroidal target fiducial volume, limited by radii a and $a + d$ and of length l (inside and outside of which one can imagine a tracking system, surrounded on the outside by a photon detecting system – e.g. lead–Sci–Fi sandwiches – and a superconducting, solenoidal coil to provide the *moderate* magnetic field \mathbf{B} needed for momentum measurements), filled with a gas at close to atmospheric pressure. For the already existing detector KLOE², we have the additional benefit that the gas chamber is fully wired, providing thus a tracking of the charged particles akin to the one available in the bubble chambers of old, but without the nuisance of the huge dead times of these latter.

One must convert the usual, fixed-target expression for reaction rates to a spherical geometry, and also include kaon decays in flight, getting (for $\mathbf{B} = 0$ or K_L^0 's: the general case can be easily treated with slight modifications)

$$dN_r = \left[\frac{1}{\rho^2} \left(\frac{3}{8\pi} \right) (L\sigma_\phi B_\phi) \sin^2 \theta e^{-\rho/\lambda} \right] \sigma_r \rho_t (\rho^2 d\rho \sin \theta d\theta d\phi) , \quad (1)$$

with ρ , θ and ϕ spherical coordinates (with the z -axis oriented along the beam direction), L the machine luminosity, σ_ϕ the annihilation cross section at the ϕ -resonance peak, B_ϕ the ϕ branching ratio into the desired mode (either $K^+ K^-$ or $K_L K_S$), σ_r the reaction cross section for the process considered, ρ_t the target *nuclear* density, and $\lambda = p_K \tau_K / m_K$ the decay length (respectively of 0.954 m for K^\pm 's and of 3.429 m for K_L 's) at the ϕ -resonance momenta.

Integrating over the fiducial volume, the reaction rate can be cast into the simple formula

$$N_r = \frac{3\pi}{4} r d (L\sigma_\phi B_\phi) \rho_t \sigma_r , \quad (2)$$

with both geometrical acceptance and kaon decay in flight thrown into the “reduction factor” r , which we have estimated to take the values 0.50 for K^\pm 's and 0.72 for K_L 's for a fiducial volume defined by $a = 10$ cm , $d = 50$ cm and $L = 1$ m , to

represent a “person-sized” detector, fitting in DAΦNE’s interaction regions. The factors would be closer to unity for a detector the size of KLOE: the parameter most influential on r is of course a as long as l is at least comparable with the decay lengths λ , due to the angular distribution of the produced kaons; besides, for K^\pm r increases almost linearly but slowly with increasing field B , due to the interplay of the increased path length inside the fiducial volume on one side, and of the particle decays on the other.

Due to the rather sorry state of our experimental informations in the energy region relevant for DAΦNE, where only data on hydrogen are available, we are able to give reliable estimates for the rates only for H_2 : from the *best available* phenomenological analysis (still that of J.K. Kim, dated 1966–1967¹²) one can *roughly estimate* the corrections to be applied (in the impulse approximation only) to other, light targets such as D_2 , ^4He or ^3He .

This gives, for a target volume filled by an almost ideal gas at room temperature (such as $^4\text{He}/^3\text{He}$ or H_2/D_2), the rates for K^\pm –initiated processes

$$N_r = p(\text{atm}) \times \sigma_r(\text{mb}) \times (4.0 \times 10^4 \text{ events/y}) , \quad (3)$$

for a “Snowmass year” of 10^7 s (for K_L ’s the figure in eq. (3) is about the same, because of an approximate compensation between the variations in r and B_ϕ), or, with rough estimates of the partial K^-p cross sections at the ϕ –decay momenta, to about 10^7 two–body events per year in H_2 gas at atmospheric pressure, of which about 3.6×10^6 elastic scattering events, 2.4×10^6 $\pi^+\Sigma^-$ and about 10^6 for each of the remaining four two–body channels $\pi^0\Sigma^0$, $\pi^0\Lambda$, \bar{K}^0n , and $\pi^-\Sigma^+$. The above rates are enough to measure angular distributions in all channels, and also the polarizations for the self–analyzing final–hyperon states, particularly for the decays $\Lambda \rightarrow \pi^-p$, π^0n (asymmetry $\alpha \simeq 0.64$) and $\Sigma^+ \rightarrow \pi^0p$ ($\alpha \simeq -0.98$). One could also expect a total of about 10^4 radiative–capture events, which should allow a good measurement on the *absolute* rates for these processes as well.

Such an apparatus will need: tracking for incoming and outgoing charged particles, time–of–flight measurements (for charged–particle identification), a moderate magnetic field (due to the low momenta involved) for momentum measurements, and a system of converters plus scintillators for photon detection and subsequent

geometrical reconstruction of π^0 and Σ^0 decays, amounting thus to a rather simple (on today's particle-physics scale), not too costly apparatus. Mentioning costs, we wish to point out that DAΦNE, though giving the experimenters a very small momentum range, saves them the cost of the *separate* tagging system needed to reject contaminations in a *conventional* low-energy, fixed-target experiment⁹.

The above formulæ for K^\pm rates do not include particle losses in the beam-pipe wall and in the internal tracking system, which were assumed sufficiently thin (e. g. of a few hundred μm of low- Z material, such as carbon fibers or Mylar), nor rescattering effects in a nuclear target such as ^4He . We have indeed checked that, due to the shape of the angular distribution of the kaons, particle losses are contained (mostly at small angles, where K -production is negligible, and events would anyhow be hard to be fully reconstructed), and momentum losses flat around $\theta = \pi/2$ (where most of the K^\pm 's are produced): even for a total thickness of the above-mentioned materials of 1 mm , kaon momenta do not decrease below 100 MeV/c and losses do not grow beyond a few percents. Rather, one could exploit such a thickness as a low-momentum, thin moderator, to span the interesting region just above the charge-exchange threshold at $p_L(K^-) \simeq 90 \text{ MeV}/c$, measurements which would add precious, additional constraints on low-energy amplitude analyses¹³.

We have presented the above simplified estimates to show that acceptable rates can be achieved, orders of magnitude above those of existing data at about the same momentum, *i.e.* to the lowest-energy points of the British-Polish Track-Sensitive Target (TST) Collaboration, taken in the mid and late seventies at the (too hastily closed down) NIMROD accelerator¹⁴.

Since losses do not affect K_L 's, a detector of the kind sketched above, similar in geometry to the one proposed by T. Bressani⁹ to do K^+ -nucleus scattering and hypernuclear experiments, could be used without any problem to study low-energy $K_L \rightarrow K_S$ regeneration and charge-exchange in gaseous targets, providing essential information for this kind of phenomena.

We wish to add that a DAΦNE detector dedicated to kaon experiments on gaseous H_2 and D_2 can continue its active life, without substantial changes, to measure K^{+-} , K^{-} , and K_L^0 -interactions on heavier gases as well (He , N_2 , O_2 , Ne , Ar , Kr , Xe), exploring not only the properly nuclear aspects of these interactions,

such as nucleon swelling in nuclei¹⁵, but also producing $\pi\Sigma$, $\pi\Lambda$ and $\pi\pi\Lambda$ systems at invariant masses below the elastic $\bar{K}N$ threshold in the so-called unphysical region, with statistics substantially higher than those now available¹⁶, due to the $\simeq 4\pi$ geometry allowed by a colliding-beam-machine detector.

3. Impact of DAΦNE on baryon spectroscopy: the states $\Lambda(1405)$ and $\Sigma(1385)$.

At low momenta, comparable to those of the kaons from DAΦNE, we have data from low-statistics experiments, mostly hydrogen bubble-chamber ones on K^-p (and K^-d) interactions^{14,18} (dating from the early sixties through the late seventies), plus scant data from K_L interactions and K_S regeneration on hydrogen¹⁹.

The inelastic channels, open at a laboratory energy $\omega = \frac{1}{2}M_\phi$ (for K^\pm 's the value of ω at the interaction point has to include ionization energy losses as well), are the two-body ones $\pi\Lambda$ and $\pi\Sigma$ (in all possible charge states), plus the three-body ones $\pi\pi\Lambda$ and (marginally) $\pi\pi\Sigma$ for K^- or K_L interacting with nucleons: K^+ -initiated processes are (apart from charge exchange) purely elastic in this energy region.

For interactions in hydrogen, the c.m. energy is limited by momentum conservation to the initial one, equal (neglecting energy losses) to $w = (m_p^2 + \mu_K^2 + m_p M_\phi)^{1/2}$, or 1442.4 MeV for incident K^\pm 's and 1443.8 MeV for incident K_L 's. As already mentioned, energy losses for charged kaons can be exploited (using the inner parts of the detector as a moderator) to explore K^-p interactions in a *limited* momentum range, down to the charge-exchange threshold at $w = 1437.2$ MeV, corresponding to a K^- laboratory momentum of about 90 MeV/c.

For interactions in nuclei, momentum can be carried away by spectator nucleons, and the inelastic channels can be explored down to threshold. The possibility of reaching energies below the $\bar{K}N$ threshold allows exploration of the unphysical region, containing two resonances, the $I = 0$, S -wave $\Lambda(1405)$ and the $I = 1$, $J^P = \frac{3}{2}^+$ P -wave $\Sigma(1385)$, observed mostly in production experiments (and, in the first case, in very limited statistics ones¹⁶): the information on their couplings to the $\bar{K}N$ channel relies *entirely* on extrapolations of the low-energy $\bar{K}N$ data. The

coupling of the $\Sigma(1385)$ to the $\bar{K}N$ channel, for instance, can be determined via forward dispersion relations involving the total sum of data collected at $t \simeq 0$, but still with uncertainties which are, *at their best*, still of the order of 50 % of the flavour- $SU(3)$ symmetry prediction²⁰; as for the $\Lambda(1405)$, even its spectroscopic classification is an open problem, *vis-à-vis* the paucity and (lack of) quality of the best available data²¹. We could add that recently even the presence of a second state with the same quantum number has been claimed²², and to prove (or disprove) such a claim would of course be rather important for the role the state has both for kaonic atoms and the determination of the low-energy parameters of the kaon-nucleon interactions.

A formation experiment on *bound* nucleons, in an (almost) 4π apparatus with good efficiency and resolution for low-momentum γ 's (such as KLOE²), can measure a channel such as $K^-p \rightarrow \pi^0\Sigma^0$ (above threshold), or $K^-d \rightarrow \pi^0\Sigma^0n_s$ (both above and below threshold), which is pure $I = 0$: up to now all analyses on the $\Lambda(1405)$ have been limited to charged channels¹⁶, and assumed the $I = 1$ contamination to be either negligible or smooth and non-interfering with the resonance signal. Since the models proposed for the $\Lambda(1405)$ differ mostly in the details of the resonance shape, rather than in its couplings, and it is precisely the shape which could be changed even by a moderate interference with an $I = 1$ background, such measurements would be decisive. Having in the same apparatus and at almost the same energy *tagged* K^- and K_L produced at the same point, one can further separate $I = 0$ and $I = 1$ channels with a minimum of systematic uncertainties, by measuring all channels $K_Lp \rightarrow \pi^0\Sigma^+$, $\pi^+\Sigma^0$ and $K^-p \rightarrow \pi^-\Sigma^+$, $\pi^+\Sigma^-$, besides, of course, the above-mentioned, pure $I = 0$, $K^-p \rightarrow \pi^0\Sigma^0$ one. It must be noted that the recent claim for *two* $\Lambda(1405)$ states²² is based on a *very low-statistics measurement*²³ of the reaction $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ (analysed, we incidentally add, *without* inclusion of the well-known low-mass enhancement in the $I = J = 0$ $\pi\pi$ channel, sometimes known as the σ -meson!): an analysis of *all* $\pi\pi Y$ ($Y = \Lambda, \Sigma$) channels, possible with much higher statistics at DAΦNE, would be therefore highly desirable.

Another class of inelastic processes which are expected to be produced, at a much smaller rate, by DAΦNE's kaons are the radiative capture processes $K^-p \rightarrow \gamma\Lambda$, $\gamma\Sigma^0$ and $K_Lp \rightarrow \gamma\Sigma^+$ (both in hydrogen and deuterium), and $K^-n \rightarrow \gamma\Sigma^-$

and $K_L n \rightarrow \gamma \Lambda$, $\gamma \Sigma^0$ (only in deuterium). Up to now only searches for photons emitted after stops of K^- 's in liquid hydrogen and deuterium have been performed with some success: the spectra are dominated by photons from unreconstructed π^0 and Σ^0 decays²⁴, and separating the signals from this background poses serious difficulties, since only the photon line from the $\gamma \Lambda$ final state falls just above the endpoint of the photons from π^0 decays in the $\pi^0 \Lambda$ final state, while that from $\gamma \Sigma^0$ falls right on top of the latter. Indeed these experiments were able to produce only an estimate of the respective branching ratios²⁵.

The 4π geometry possible at DAΦNE, combined with the “transparency” of a KLOE-like apparatus², its high efficiency for photon detection and its good resolution for spatial reconstruction of the events, should make possible (in an H_2/D_2 experiment) the full identification of the final states and therefore the measurement of the absolute cross sections for these processes, although in flight and not at rest.

Present data²⁴ indicate branching ratios around 0.9×10^{-3} for $K^- p \rightarrow \gamma \Lambda$ and 1.4×10^{-3} for $K^- p \rightarrow \gamma \Sigma^0$, with errors of the order of 15 % on both: most models²⁶ give the first rate larger than the second, with both values consistently higher than the observed ones. Only a cloudy-bag-model²⁷ exhibits the trend appearing (although only at a 2σ -level, and therefore waiting for confirmation by better data) from the first experimental determinations, but this is the only respect in which it agrees with the data, still giving branching ratios larger than observations by a factor two.

Data are also interpretable in terms of $\Lambda(1405)$ electromagnetic transition moments²⁵: this interpretation is clearly sensitive to the interference between the decay of this state and all other contributions. An extraction of the $\Lambda(1405)$ moments freer of these uncertainties would require measurements of $\gamma \Lambda$ and $\gamma \Sigma$ (if possible, in different charge states) over the unphysical region, using (gaseous) deuterium or helium as a target. Rates are expected to be of the order of 10^4 *events/y* only, but such a low rate would correspond to better statistics than those of the best experiment performed on the $\Lambda(1405) \rightarrow \pi \Sigma$ decay spectrum¹⁶.

4. Final recommendations.

A first, modest proposal would therefore be the following: before building a *dedicated apparatus* for low-energy experiments on various gaseous targets, one could equip the existing experiment KLOE with a less restrictive trigger, that could select the interactions of anti-kaons (tagged by their antiparticles on the opposite side, be they either K^+ 's or K_S^0 's) with the gas filling the chamber and reconstruct off-line the pion-hyperon, pion-pion-hyperon and single- γ -hyperon spectra for *all* charge combinations. Such data would contain both the $\Lambda(1405)$ and the $\Sigma(1385)$, including their interference, plus the effects of rescattering *inside* the remainder of the ^4He target. The latter will further feed – via charge-exchange processes – also such “exotic” combinations as $\Sigma^\pm\pi^\pm$, allowing a better understanding of the nuclear-medium distortions on the “elementary” processes $\bar{K}N \rightarrow \pi Y$, $\bar{K}N \rightarrow \pi\pi Y$ and $\bar{K}N \rightarrow \gamma Y$.

We wish to end underlining how KLOE (or a similar, scaled down apparatus) is unique for such a scope: the need for a good efficiency and high resolution for low-energy γ 's (motivated for KLOE by decays such as $\phi \rightarrow \gamma(a_0, f_0)$ and the reconstruction of very low-momentum π^0 's) allows also the identification and reconstruction of Σ^0 's through their decay to $\Lambda\gamma$, virtually impossible in any other detector with an almost 100 % efficiency. On the other hand, the very high efficiency for γ detection, combined with the high intensity of the source and the ease with which one can discriminate between kaons and pions (not to mention leptons) from the ϕ decays, allows an unprecedentedly clean determination of radiative capture events (even if in a slightly more complex target than hydrogen or deuterium).

As a closing remark one can add that contaminations due to the presence of a small admixture of other gases in helium, or to the tungsten wires running across the chamber, are not that important for the mass spectra (they amount to – small – distortions in the nucleon distribution functions, which the “elementary” amplitudes have to be convoluted with, with respect to those for pure ^4He), and even less for the ratio of γY (or $\pi\pi Y$) to πY spectra.

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